1995-09

Scheduling Army deployments to two nearly simultaneous major regional conflicts

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http://hdl.handle.net/10945/35101

NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

THESIS

SCHEDULING ARMY DEPLOYMENTS TO TWO NEARLY SIMULTANEOUS MAJOR REGIONAL CONFLICTS

by

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September 1995

Thesis Advisor: R. Kevin Wood

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE September 1995

3. REPORT TYPE AND DATES COVERED Master's Thesis

4. TITLE AND SUBTITLE SCHEDULING ARMY DEPLOYMENTS TO TWO NEARLY SIMULTANEOUS MAJOR REGIONAL CONFLICTS

5. FUNDING NUMBERS

6. AUTHOR(S) Steven M. Aviles

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(maximum 200 words)*

The United States military strategy is currently focusing on Major Regional Conflicts (MRCs), rather than on a single, major war. The Plural MRC Model, PaMM, is an integer programming model and solution procedure that develops deployment schedules for active duty Army combat divisions to two nearly simultaneous MRCs without perfect information regarding the second MRC. PaMM develops the deployment schedules using a sequential heuristic: It first solves the optimal deployment schedules for a single MRC, fixes all movement that occurs before the hypothesized start date of a second MRC, and solves the resulting problem for both MRCs. The sequential technique is robust: Using a hypothetical scenario where all divisions for the first MRC are required within the first 30 days, PaMM is run six times, varying the time difference between the start dates of the MRCs from 10 to 60 days. The deployment schedules for the first MRC are comparable to the "optimal" deployment schedules created using perfect information.

14. SUBJECT TERMS Dual MRC, Multi-commodity transshipment, Sequential Solving Model

15. NUMBER OF PAGES 65

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18 298-102

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SCHEDULING ARMY DEPLOYMENTS TO TWO NEARLY SIMULTANEOUS MAJOR REGIONAL CONFLICTS

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Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

The United States military strategy is currently focusing on Major Regional Conflicts (MRCs), rather than on a single, major war. The Plural MRC Model, PaMM, is an integer programming model and solution procedure that develops deployment schedules for active duty Army combat divisions to two nearly simultaneous MRCs without perfect information regarding the second MRC. PaMM develops the deployment schedules using a sequential heuristic: It first solves the optimal deployment schedules for a single MRC, fixes all movement that occurs before the hypothesized start date of a second MRC, and solves the resulting problem for both MRCs. The sequential technique is robust: Using a hypothetical scenario where all divisions for the first MRC are required within the first 30 days, PaMM is run six times, varying the time difference between the start dates of the MRCs form 10 to 60 days. The deployment schedules for the first MRC are comparable to the "optimal" deployment schedules created using perfect information.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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EXECUTIVE SUMMARY

The National Military Strategy of the United States of America, February 1995, requires the United States military "to defeat potential enemies in major conflicts that may occur nearly simultaneously in two different regions." Major conflicts that can occur in different regions throughout the world are referred to as "Major Regional Conflicts" (MRCs). The new focus on MRCs, and the decrease in number of Army divisions from eighteen to ten, requires Army planners to develop a methodology for creating effective deployment schedules for troops and equipment to two different, but nearly simultaneous MRCs. This thesis develops the Plural MRC Model (PaMM), an integer programming model and solution procedure that will assist Army planners in developing such schedules.

PaMM develops deployment schedules for active duty combat units to two nearly simultaneous MRCs. Unit size is battalion level for an aviation unit, and brigade/regiment level for other units. A single unit schedule describes when a unit will leave its home station, when it will load onboard a ship, when it will leave its port of embarkation, when it will arrive and unload at its port of debarkation and when it will travel to its theater of operations. "MRC schedules" will refer to the collection of unit schedules associated with a specific MRC.

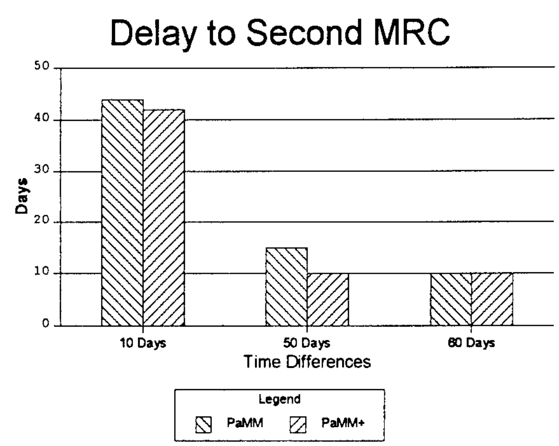
PaMM is intended for use with imperfect information regarding the start date and location of a second MRC. Planners may have a good idea about such a contingency, but it cannot be assumed their

information will be perfect. However, to create a baseline for measuring the quality of PaMM's deployment schedules, PaMM can be used employing perfect information. PaMM plus perfect information, PaMM+, creates optimal deployment schedules assuming start dates and locations of both MRCs are known. PaMM can then be described as a sequential heuristic applied to PaMM+ to account for imperfect information about a second MRC.

The mathematical formulations for PaMM+ and PaMM are the same, but the way they create deployment schedules is different. PaMM+ creates optimal deployment schedules for both MRCs assuming perfect information. PaMM creates an optimal deployment schedule to the first MRC assuming perfect information about the first MRC only. It fixes all movement that occurs before the assumed start date of the second MRC, and then creates schedules for both MRCs from that date. Planners can make multiple runs of PaMM, varying the time difference between MRCs (and possibly, locations of the second MRC), to gain insight into how different start dates of a possible second MRC affect the deployment schedules of the first MRC. The objective of both models is to minimize a function of the time between the desired unit arrival dates and the actual arrival dates, i.e., delay.

PaMM is tested using a hypothetical scenario where a rebel uprising in Korea (the first MRC) is followed by an attack on Saudi Arabia (the second MRC). The hypothesized time differences between the start dates of the two MRCs are 10, 20, 30, 40, 50, or 60 days. For the single MRC, PaMM creates deployment schedules with a delay of 135 days.

For the first MRC, PaMM creates the same deployment schedules for each time difference. PaMM+ creates only two substantially different schedules for the six time differences. Where time differences are 20, 30 and 40 days, PaMM+ creates deployment schedules very similar to PaMM. However, with time differences of 10, 50, and 60 days, the deployment schedules are different. Since PaMM's results are different for these time differences, the delay to the second MRC is compared for PaMM and PaMM+:



For time differences of 10, 50 and 60 days, PaMM+'s use of perfect information decreases delay by only 2, 5 and 0 days, respectively. Since the savings to the second MRC are not significant, PaMM's deployment schedules are good and can be used with confidence.

This thesis shows that for this test case, Army planners can use PaMM to create good deployment schedules for two nearly simultaneous MRCs. It is recommended that Army planners test PaMM on other scenarios to confirm its usefulness. If no difficulties are encountered, PaMM should be used when planning deployment schedules for a single and dual-MRC scenarios.

I. INTRODUCTION

The National Military Strategy of the United States of America, February 1995, requires the United States military "to defeat potential enemies in major conflicts that may occur nearly simultaneously in two different regions." Major conflicts that can occur in different regions throughout the world are referred to as "Major Regional Conflicts" (MRCs). The new focus on MRCs, and the decrease in number of Army divisions from eighteen to ten, requires Army planners to develop a methodology for creating effective deployment schedules for troops and equipment to two different, but nearly simultaneous MRCs. This thesis develops the Plural MRC Model (PaMM), an integer programming model and solution procedure that will assist Army planners in developing such schedules.

A. PURPOSE

To help in planning to win two nearly simultaneous MRCs, US Army planners need to develop contingency unit deployment schedules for possible single MRCs that are flexible enough that they can be easily extended to a second MRC, if and when a second MRC begins. A single unit schedule describes when a unit will leave its home station, when it will load onboard a ship, when it will leave its port of embarkation, when it will arrive and unload at its port of debarkation and when it will travel to its theater of operations. "MRC schedules" will refer to the collection of unit schedules associated with a specific MRC.

One problem with developing dual-MRC deployment schedules is that when a first MRC breaks out there will typically be no way of knowing if, or when a second MRC will

occur. Planners do not want lives lost because they hold troops and equipment in reserve for a second MRC that never materializes. On the other hand, if a second MRC does occur, they do not want lives lost because they could not deploy troops and equipment to the second MRC quickly enough. They need a model that develops unit deployment schedules that are good for a single MRC, and that can be extended to cover both MRCs well.

With the recent downsizing of the Army from eighteen divisions to ten divisions, the Army has significantly reduced its "forward deployed units" (units permanently stationed overseas). Therefore, in a two-MRC scenario, more units must be deployed overseas than before. As a result, the tools used for planning deployments in the old, "Cold War" environment are no longer appropriate.

During the Cold War era, if a conflict broke out, the Army already had units stationed where it expected to fight, so planners had to consider only a modest number of overseas deployments when creating deployment schedules. With fewer units needing to be deployed overseas, and enough forces to handle any contingency that might occur, Army planners could easily predesignate units to destinations in creating their deployment schedules. Predesignation of units to destinations was not incorrect, in and of itself. However, even then, the assignment of interchangeable brigades (brigades of the same type or having similar capabilities) to different arrival dates at the theater could be less than optimal: Which unit was the best unit to send first?

The possibility of creating bad deployment schedules using the old methodology is even greater with a smaller-Army responding to a two-MRC scenario, where more forces need to be deployed overseas. In this new scenario,

planners must decide which units to send where, and when. This extra degree of freedom makes predesignation of units to destinations and arrival times even more restrictive and likely to lead to poor deployment schedules.

To address the deficiencies of the old methodology in the new scenario, this thesis develops PaMM, an integer programming model and solution procedure that develops deployment schedules for active duty Army combat units to two nearly simultaneous MRCs. Subject to restrictions necessary because of uncertainty about a second MRC, PaMM will choose the best unit to send to the right theater at the right time. PaMM's objective is to minimize a function of the delay between the day a unit arrives at the MRC, and the day it is needed. In PaMM, unit size is battalion level for an aviation unit, and brigade/regiment level for all other units. PaMM is meant to help plan for a possible dual-MRC scenario. However, if a MRC is already underway, PaMM can develop possible schedules for a second MRC, by hypothesizing start dates for the second MRC.

If planners assume they will have perfect information regarding the outbreak of a second MRC at the time a first MRC begins, they will be able to create optimal deployment schedules for both MRCs. PaMM plus perfect information, "PaMM+," creates such schedules. However, it is unlikely planners will have perfect information, so PaMM takes this into account. That is, PaMM is based on the assumption that planners will probably know where a second MRC will occur, if it does, but that planners will not know the exact date it will begin. Therefore, PaMM is used to explore possible deployment schedules under various time differences. To do this, PaMM is employed as a sequential heuristic as follows: PaMM first creates optimal deployment schedules for Army

units moving to a single MRC, fixes all movement that occurs before the hypothesized start date of a second MRC, and then creates optimal deployment schedules for the rest of the first MRC and all of the second MRC. If planners are uncertain about where a second MRC might occur, they can run instances of PaMM for each possible second MRC location and start date.

Planners can determine the robustness of the schedules PaMM creates by comparing them to the optimal deployment schedules PaMM+ creates. If there is little or no difference, planners can deploy units to the single/first MRC knowing they will not be significantly affecting the deployment schedules to a possible second MRC. If the schedules differ greatly, planners can then compare the total delay to the second MRC. If the optimal schedules developed by PaMM+ do not significantly reduce the delay to the second MRC, then planners can still use the schedules developed by PaMM knowing that if a second MRC does occur, they will be able to get units to the second MRC almost optimally. If the decrease in delay achieved with PaMM+ is significant, planners should be concerned, but PaMM can be used to further explore tradeoffs between different deployment schedules, at least in an *ad hoc* fashion.

Formal stochastic programming techniques might be appropriate for creating unit deployment schedules to two MRCs. For instance, a two-stage stochastic model could be formulated with a given initial MRC, but having multiple possible scenarios (locations and dates) for a second MRC. Probabilities of occurrence would be associated with each second MRC scenario and the objective of the model would be to minimize some function of expected delay in meeting demands. However, the author believes that at this time (a)

the data to support such a model does not exist, (b) Army planners would be uncomfortable making the assumptions necessary to use such a model, and (c) such a model would be extremely hard to solve. On the other hand, (a) the data to support PaMM exists, (b) Army planners should have little trouble believing the results obtained using PaMM's conservative assumptions, and (c) this thesis demonstrates that both PaMM and PaMM+ are readily solvable.

B. BACKGROUND

Currently, the Army Concepts Analysis Agency (CAA) uses TRANSMO, a simulation model, to estimate realistic deployment schedules.(CAA, 1985) TRANSMO represents units as packages based upon the amount of cargo a unit needs moved, and orders these packages based upon the day each package is required in theater. The day the package is required is the "latest arrival date" (LAD) of the package. TRANSMO creates deployment schedules by using a heuristic scheduling algorithm intended to maximize the utilization of lift assets to move these packages.

To use TRANSMO, planners must input the destination and LAD of each package. For an Army with numerous divisions stationed overseas, and focused on a single threat, specifying destinations and LADs was not a problem because fewer units needed to be deployed, and there were enough units to cover any contingency that might arise. However, with a smaller Army and more forces needing to be deployed, and with the possibility of sending units to two different theaters, planners need a scheduling methodology that creates good schedules without requiring perfect guesses about where and when each unit should be sent.

C. SCOPE, LIMITATIONS AND ASSUMPTIONS

The main thrust of the thesis is to develop a deployment scheduling model, PaMM, for active duty combat units going to two nearly simultaneous MRCs. The study will not try to determine how many or what type of units the Army needs, but rather, the best way to deploy these units. In this thesis, PaMM is used as a planning tool to generate deployment schedules for a possible dual-MRC scenario. However, if an MRC is already underway, PaMM can be used to create deployment schedules to a probable second MRC for any possible start date.

PaMM and PaMM+ consist of two interrelated network models: a unit movement network model, and a ship movement network model. The unit movement network uses home stations, ports and MRCs as nodes with port and MRC nodes expanded by time, i.e., replicated over time to represent location and time period. The arcs of this model represent the possible movement of units between locations and the time that these movements occur. The nodes of the ship movement network represent ports expanded by time. The arcs represent the possible movement of ships, in time and space, from one port to another. Constraints link the unit and ship movement networks to ensure that a unit does not travel from one port to another unless ships with sufficient capacity to carry the unit move between the same ports at the same time as the units.

PaMM+ creates its deployment schedules by minimizing a function of the delay between when units are needed at the MRCs, and when they actually arrive. PaMM's objective is essentially the same, except that the minimization is restricted by the solution procedure. The dates when units of specified types are needed will come from the Commander-

in-Chief's (CinC's) operation plan. This plan states the days on which the CinC needs specified types of units to arrive at the MRC, in order for him to successfully complete his mission. Since the resolution of the operation plan is assumed to be in days, the resolutions of PaMM and PaMM+ are in days.

For simplicity, the research in this thesis is limited to only active duty combat units. However, planners could include Army Reserve and Army National Guard units. The research also considers only three types of transportation ships: fast sealift ships (FSS), roll-on-roll-off (RORO) and breakbulk (BB). Other ship types could be easily added. This thesis only considers two MRCs since this is the concern of our National Military Strategy. The model, however, could be extended to handle more than two. Some other basic assumptions and simplifications are described next.

The US Army is assumed to have only ten active duty divisions, and the total number of divisions demanded at both MRCs will not exceed ten. The initial location and division type are known for each division. Since all ten divisions might be needed to deploy, all units are considered to have the same deployment priority level. Each unit will deploy to only one possible POE, and all the brigades from one division will deploy to the same theater. For simplicity, all ships are assumed to move at the same speed and the number of ships available remains constant, i.e., there are no losses due to mechanical breakdown or interdiction. Each theater is assumed to have one POD. The time for all units to load is two days and to unload two days. The extra time needed to prepare helicopters for sea

travel, and then prepare them for use in theater once they arrive, will be added to the travel time of an aviation unit to a POE and the travel time from POD to theater.

D. LITERATURE REVIEW

In recent years, the US Army has been using computers to help determine the best way to move troops to conflicts. Two of the most popular models used by the Army have been the Model for Intertheater Deployment by Air and Sea (MIDAS) and the US Army Concepts Analysis Agency (CAA) Transportation Model TRANSMO. Both of these models are described in CAA's Transportation Model Comparison (TRAC)(CAA, 1985) whose purpose was "to provide a definitive comparison of ...TRANSMO and ...MIDAS."

To compare these models, the study first described each model. For MIDAS, "the data describing each unit include ...a Required Delivery Date, and a planned destination." For TRANSMO, "the main inputs of the model are: ... the POD, [and] the date cargo is due at the POD..." (brackets added by author). In both models, the final destination of every unit, and the date by which units are needed are specified in the data. This means that to develop optimal deployment schedules, planners must make perfect decisions regarding unit destinations before the model is ever run. It is not likely that their decisions will be perfect. Better schedules may be developed by a model that has the flexibility to choose which unit to send to which destination. This flexibility is incorporated in PaMM.

Glaser (1991) develops an integer programming model for scheduling the deployment of sea mines to different areas. Her model uses two interrelated networks, a network for mine movement and a network for the flow of transportation assets

to carry the mines. Constraints connecting the two networks ensure that mines do not move unless there are transportation assets to move them. She shows how two interrelated networks can be used to model movements of material from supply points to demand points, using transportation assets that can return to the original or different supply points to pick-up and move more material to meet other demands. PaMM also uses two interrelated networks where units are the material being moved and ships are the transportation assets. However, PaMM transports multiple commodities, i.e., multiple unit types, while Glaser's model only transports a single commodity, mines.

A concurrent study related to this thesis is Pagonis, 1995. However, Pagonis' main concern is ship schedules for the transportation of resources to two MRCs. His study does not develop deployment schedules for units, but uses unit deployment schedules as input to develop near-optimal ship schedules to carry these units to the different MRCs. Although generic ship schedules are produced by PaMM, it should be possible to use the unit deployment schedules generated by PaMM as input to the Pagonis model to obtain more detailed ship schedules.

E. OUTLINE

The thesis is divided into four chapters. The first chapter is the introduction and identifies the purpose and background of the thesis. The second chapter gives a general description of PaMM and PaMM+, gives the mathematical formulation and then discusses the formulation in detail. The third chapter gives computational results for an unclassified test scenario and analyzes and discusses

the results. The results obtained from PaMM are compared to the "optimal" deployment schedules developed by PaMM+. The final chapter gives conclusions and interprets results.

II. MODEL FORMULATION

The formulations for PaMM+ and PaMM are exactly the same. However, the way they create deployment schedules is different. PaMM+ creates optimal deployment schedules for both MRCs assuming perfect information. PaMM creates optimal deployment schedules to the first MRC assuming perfect information about the first MRC only. It fixes all movement that occurs before the hypothesized start of a second MRC, and then creates optimal schedules for the remainder of the first MRC and all of the second MRC. (This will typically be repeated for multiple hypothesized start dates, and possibly locations, for the second MRC.) This chapter gives conceptual and detailed mathematical descriptions for PaMM and PaMM+.

A. GENERAL DESCRIPTION

PaMM must be able to handle different types of units moving to meet demands in different theaters at different times. To accomplish this, each unit starts at its home station, moves to the closest POE, and then deploys to either theater to satisfy demand. Once the ships have been offloaded at the POD, the ships may move to a new POE to pick up an available unit.

To model the above situation, two interrelated network models are used: a unit movement network, and a ship movement network. Only the unit movement network has a demand associated with it. The demand for each MRC comes from the CinC's operation plan. It represents the days by which specific types of units should have arrived at the MRCs. Failure to meet a demand on time incurs a penalty of $(t'-t)^{\alpha}$, where t' is the actual arrived time (day), t is the

desired arrival time and $\alpha > 1$. The parameter α is greater than one so that the later a demand is met, the more significant the marginal cost.

Nodes in the unit movement network correspond to division home stations, POEs, PODs and MRCs. The POE, POD, and MRC nodes are expanded by time. Arcs are identified by the possible routes between nodes, and the time a unit leaves its origin and arrives at its destination. The number of units in a division stationed at a particular home station is the supply available for the unit movement network. An example of a simplified unit movement network for a single division, POE, POD and MRC, is displayed in Figure 1.

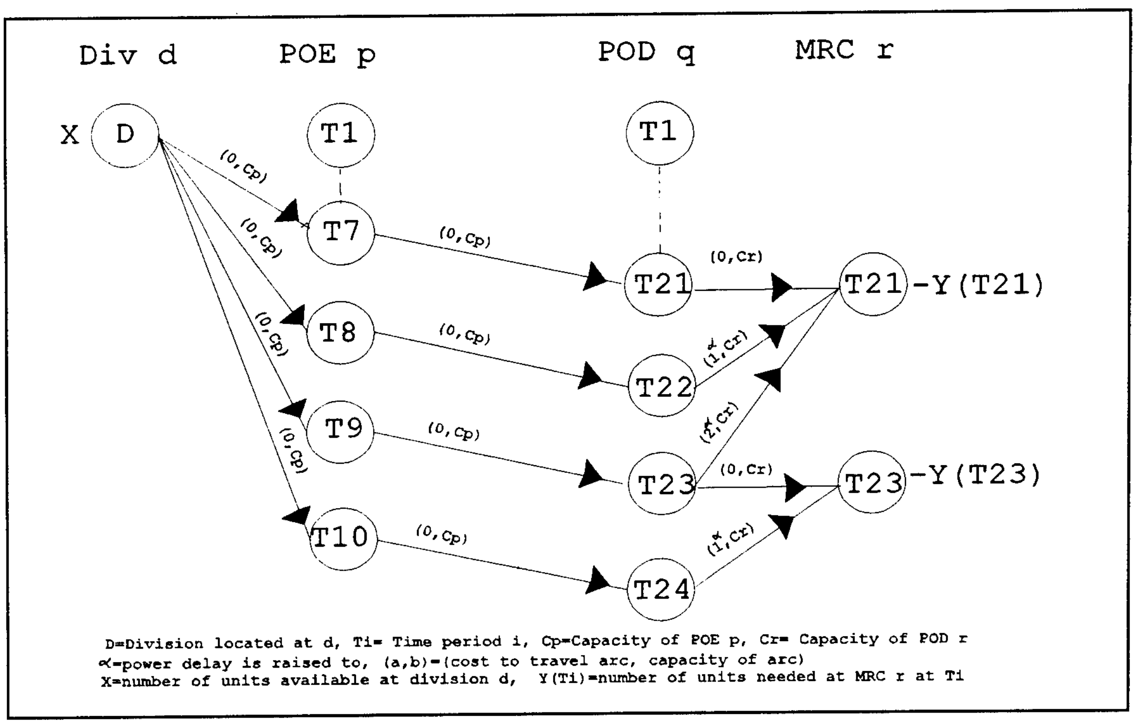


Figure 1. Example of the Unit Movement Network

As can be seen in Figure 1, a unit starts at its home station and moves to a POE at some time *t*. From the POE, a unit will move to a POD, and then to the associated MRC to meet some demand. The arcs represent movement from one location to another and the time, in days, it takes to make that movement. It is assumed that a unit stays at its home station until there are ships with enough carrying capacity at the POE ready to transport it to a POD, it will be able to unload at the POD, and move into the MRC. This limits the amount of time a unit spends in transit.

The nodes of the ship movement network represent POES and PODs, expanded by time. The arcs represent possible routes and times ships can take between POEs and PODs. Ships are allowed to wait at POEs for the next available unit, but will not move to a POD unless they will be able to unload immediately. A ship movement network for a single POE and single POD is shown in Figure 2. The two networks are

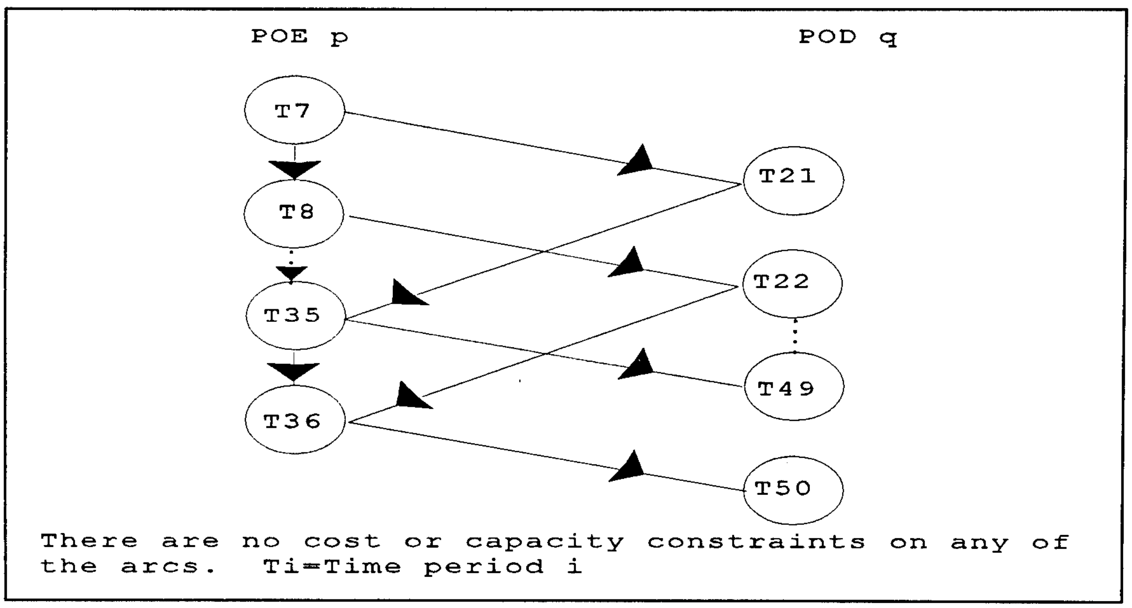


Figure 2. Example of the Ship Movement Network

connected by constraints that ensure units do not move on an arc from a POE to a POD unless ships with enough carrying capacity also move along the same route at the same time.

B. DESCRIPTION OF THE UNIT MOVEMENT NETWORK

The unit movement network models possible movements of active duty Army combat units to the different MRCs. The nodes of the network consist of fourteen division nodes, six POE nodes, two POD nodes and two MRC nodes. The POE, POD, and MRC nodes are expanded by time. The arcs of the network correspond to the movement between nodes, and the time that the movement occurs.

The fourteen division nodes, identified by a division and the location where it is stationed, are the supply nodes of the network. If more than one division is stationed at the same location, or a division has its brigades stationed at different locations, separate division nodes are used. The fourteen division nodes are:

- 1 = Fort Bliss(1ACR)
- 2 = Fort Hood(2AD)
- 3 = Fort Hood(1 Cav)
- 4 = Fort Lewis(2ID)
- 5 = Hawaii(25LID)
- 6 = Fort Campbell(Aviation Brigade)
- 7 = Fort Campbell(101 Air Assault)
- 8 = Fort Bragg(82 Airborne)
- 9 = Fort Stewart(24 Mech)
- 10 = Fort Drum(10LID)
- 11 = Germany(1AD)
- 12 = Germany(3 Mech)
- 13 = Fort Riley(1AD)
- 14 = Fort Riley(3 Mech)

The units, identified by division and type of unit, start at their division node at time period 1. There are six different type of units:

- 1 = heavy
- 2 = light infantry
- 3 = aviation
- 4 = air assault
- 5 = airborne
- 6 = armored cavalry regiment

The amount of supply at each division equals the number of units stationed there. At some time *t*, units will leave their division location and arrive at the closest POE.

Each division node is connected only to the closest POE. Time to move from division location to POE is fixed and is solely dependent upon the distance between the home station and the POE, with one exception. Aviation units have an extra eight days added to their travel time to simulate the time needed to "wrap" (prepare for transport) their helicopters. The variable W_{pdt} represents the number of units moving from division *d*, arriving at POE *p*, at time period *t*. Units will not leave their home station until they will be able to load on ships at the POE.

The six POE nodes correspond to areas throughout the world that US Army units can embark from. These are not necessarily single ports, but areas where at least one port is located. The six POEs are:

- 1 = Gulf of Mexico
- 2 = southeast United States
- 3 = northeast United States
- 4 = western United States
- 5 = Germany
- 6 = Hawaii

Units arrive at POEs and immediately begin to load onto ships.

The loading time for each unit is assumed to be two days. The number of units that are loading at one time is constrained by the berthing capacity of the POE and ship availability. These constraints are enforced by limiting

the number of units that can arrive at POE p over any two day period to $W_{pdt} + W_{pdt-1} \leq C_p$, where C_p is the total berth capacity of all ports that make up POE p.

Once a unit is loaded, it moves to a POD. To simplify PaMM's formulation, the travel time between a specific POE and a specific POD is assumed constant regardless of the type of ship used to transport the unit. The variable X_{pqdt} represents the number of units of division d, moving from POE p, arriving at POD q, at time period t.

The POD nodes correspond to all the ports in the region at which units can disembark. There is one POD node per MRC. The POD nodes are:

- 1 = northeast Asia (NEA)
- 2 = southwest Asia (SWA)

When a unit arrives at a POD it will begin to unload. Unloading, like loading is assumed to take two days regardless of the type of unit. Once a unit is unloaded it will move to the MRC theater. The berth capacity of the PODs is accounted for by limiting the number of units that can move between a POD and MRC over a two day period.

The MRC nodes are the demand nodes of the network and correspond to the region where the MRC is occurring. The MRC nodes are:

- 1 = Korea
- 2 = Saudi Arabia

All units, except aviation units, are assumed to take two days to move into the MRC. Aviation units need eight days to unwrap their helicopters, so ten days is used as their travel time to theater.

The demands of the network are defined by the type and number of units needed, when they are needed by, and where they are needed (which MRC). The demand for each MRC is determined by the Commander-in-Chief of that region. The

variable $Y_{qdt't}$ represents the number of units of division d, moving from POD q, arriving in theater at time period t', to meet a demand that was needed at time period t. If t' is greater than t, then a penalty is incurred equal to $(t'-t)^{\alpha}$. There is no penalty for units arriving early.

C. DESCRIPTION OF THE SHIP MOVEMENT NETWORK

The ship movement network moves ships from POEs to PODs, and back. The nodes of the network are POEs and PODs, expanded by time. The arcs of the network represent ship movement from one port to another, and the time that the movement occurs.

For this study, only three types of ships are used to move units. The three types of ships are:

- 1 = Fast Sealift Ship
- 2 = Roll-on roll-off
- 3 = Breakbulk

Once a ship is needed, it will load as much of a unit as it can carry at a POE and then transport it to either POD. The variable V_{pqst} represents the number of ships of type s, leaving POD p, at time period t, to go to POD q.

At time period one, all ships are stored in inventory at the POEs because the ships will not be needed until units are ready to move from POEs to PODs. The variable I_{pst} represents the number of ships of type s, in inventory at POE p, at time period t. The initial number and type of each ship at each POE, not to exceed the total number of ships of each type available, will be determined by the model based upon where the ships are needed.

Although, realistically, ships move at different speeds, to simplify PaMM, all ships are assumed to move at the same speed. This may not be a restrictive assumption since all unit types require more cargo capacity than any single ship

has available, each unit will require more than one ship for transport, these ships may be of different types, and different types of ships will often end up moving together in convoy at a single slow speed.

PaMM allows ships to wait outside of a POE, "in inventory," if a berth is not available. Once a ship moves into a berth, it will load as much of the first available unit it can carry and then transport it to its POD. Once a ship unloads at the POD, it will move back to any POE that needs a ship. The variable $V1_{qpst}$ represents the number of ships of type s, leaving POD q, at time period t, to go to POE p. The unit and ship networks are connected so that units move from a POE to a POD only when ships with enough carrying capacity are available to move them.

D. FORMULATION

The following formulation pertains to both PaMM and PaMM+.

1. Indices

d divisions - (1,2,...,14)

p POEs - (1,2,...,6)

q PODs - (1,2)

r MRCs - (1,2)

b type of unit - (1,2,...,6)

t time in days - (1,2,...,tmax)

s ship type - (1,2,3)

2. Sets

D divisions (1,2,...,14)

P POEs (1,2,...,6)

Q PODs (1,2)

R MRCs (1,2)

B type of unit (1,2,...,6)

T time in days (1,2,...,tmax)

S ships (1,2,3)

3. Subsets

$D_p \subseteq D$ divisions that can send units to port p

$D_b \subseteq D$ divisions that have type b units

$B_d \subseteq B$ unit types that can be found in division d

$B_r \subseteq B$ unit types required at MRC r

$P_d \subseteq P$ POEs that can receive units from division d

$P_q \subseteq P$ POEs that can send units to POD q

$Q_r \subseteq Q$ PODs that can send units to MRC r

$T_r \subseteq T$ times when there is a demand at MRC r

4. Data

A_d number of units of division d available

Req_{rbt} number of units required of brigade type b at time t at MRC r

$T1_{dp}$ time in days to move from division d to POE p

$T2_{pq}$ time in days to move from POE p to POD q

$T3_{dqr}$ time in days for division d to move from POD q to MRC r

C_p berth capacity at POE p

$C2_r$ berth capacity of PODs sending units to MRC r

U_s fraction of an armored unit that can be carried by ship type s

Tot_{st} number of ships available of type s at time t

Com_{db} number of units of type b in division d

Mp_d amount of cargo space required by division d divided by the amount of space required by a heavy division

Δ the time difference in days between the start date of the first and second MRC

5. Parameters

R_d the earliest time in days a unit from division d can arrive at its POE

$R1_{dq}$ the earliest time in days a unit from division d can arrive at POD q

$R2_{dr}$ the earliest time in days a unit from division d can arrive at MRC r

NLT_d the minimum time in days it takes a unit to move from division d to the nearest MRC

$NLT1_{dp}$ the minimum time in days it takes a unit from division d to move from POE p to the nearest MRC

$NLT2_{dq}$ the minimum time in days it takes a unit from division d to move from a POD q to the nearest MRC

$R3_p$ the minimum time in days it takes for any unit to move from its home station to POE p

$R4_q$ the minimum time in days it takes for any unit to move from its home station to a POD q

6. Variables

W_{pdt} number of units of division d moved to POE p at time t

X_{pqdt} number of units of division d moved from POE p to POD q at time t

$Y_{qdt't}$ number of units of division d moved from POD q at time t' to meet demand at time t

F_{rbt} number of units of type b not supplied to MRC r at time t

Bin_{qd} binary variable, = 1 if division d goes to POD q

V_{pqst} number of ships of type s moved from POE p to POD q at time t

$V1_{qpst}$ number of ships of type s moved from POD q to POE p at time t

I_{pst} number of ships of type s waiting at POE p at time t

7. Mathematical Formulation

$$Min \sum_q \sum_{d \in D_{bt}} \sum_{t'>t} \sum_{t \in T_r} [(t'-t)^{\alpha} * Y_{qdt't}] + \sum_r \sum_b \sum_{t \in T_r} [(tmax-t)^{\alpha} * F_{rbt}] + C * \sum_{d=1}^{d=12} Bin_{q1d} + \epsilon * \sum_p \sum_q \sum_s \sum_t V_{pqst} \tag{1}$$

Subject to:

$$\sum_{p \in P_d} \sum_t W_{pdt+T1_{dp}} \leq A_d \quad \forall d \tag{2}$$

$$-W_{pdt} + X_{pq1dt+T2_{pq}} + \sum_{t'=t=\Delta+T1_{dp}} X_{pq2dt'+T2_{pq}} = 0 \quad \forall\, p, d\in D_p, t \tag{3}$$

$$-\sum_{p\in P_d, p\in P_q} X_{pq1dt} + \sum_{t'\in T_r} Y_{q1dt+T3_{dqr}t'} = 0 \quad \forall\, d, q, t \tag{4}$$

$$-\sum_{q\in Q_r}\sum_{d\in D_b}\sum_{t'>R2_{dr}} Y_{qdt't} - F_{rbt} = -Req_{rbt} \quad \forall\, r, b\in B_r, t\in T_r \tag{5}$$

$$\sum_{d\in D_b} W_{pdt} + \sum_{d\in D_b} W_{pdt-1} \le C_p \quad \forall p, t>R_{dp} \tag{6}$$

$$\sum_{q}\sum_{d\in D_b}\sum_{t\in T_r} Y_{qdt't} + \sum_{q}\sum_{d\in D_b}\sum_{t\in T_r} Y_{qdt'-1t} \le C2_r \quad \forall r, t'>R2_{dr} \tag{7}$$

$$\sum_{d\in D_b} Mp_d * X_{pqdt} - \sum_{s} U_s * V_{pqst-T2_{pq}} \le 0 \quad \forall p, q, t>R4_q \tag{8}$$

$$\sum_{p\in P_d}\sum_{t>R1_{dq}} X_{pqdt} - 3 * Bin_{qd} \le 0 \quad \forall\, q, d \tag{9}$$

$$\sum_{q} Bin_{qd} - 1 \le 0 \quad \forall d \tag{10}$$

$$Bin_{qd11} - Bin_{qd13} = 0 \quad \forall\, q \tag{11}$$

$$Bin_{qd12} - Bin_{qd14} = 0 \quad \forall\, q \tag{12}$$

$$\sum_{p} I_{pst} = Tot_{st} \quad \forall\, s, t\in T_s \tag{13}$$

$$-\sum_{q}\sum_{t'>T2_{pq}+R3_p} V1_{qpst'-T2_{pq}} + \sum_{q}\sum_{t'>R4_q} V_{pqst'} - I_{pst-1} + I_{pst} = 0 \quad \forall p, s, t>T1_{dp} \tag{14}$$

$$-\sum_p V_{pqst-T2_{pq}} + \sum_p V1_{qpst} = 0 \quad \forall q,s,t>R3_p \tag{15}$$

E. DESCRIPTION OF THE FORMULATION

The primary objective of the model is to meet demands for units of specified types in each MRC on given dates while minimizing a function of delay defined as:

$$\sum_q \sum_{d\in D_b} \sum_{t'>t} \sum_{t\in T_r} [(t'-t)^{\alpha} * Y_{qdt't}]$$

where t' is the actual arrival time (day), t is the desired arrival time and $\alpha > 1$. For this thesis, $\alpha=1.5$ is used because the author feels it is slightly better to have many divisions one day late, than one division many days late. Note that if a unit arrives before it is required, i.e., $t'<t$, there is no penalty.

The second term of the objective function accounts for the possibility of demands not being met at all:

$$\sum_r \sum_b \sum_{t\in T_r} [(tmax-t)^{\alpha} * F_{rbt}]$$

where F_{rbt}, is the number of units of type b not supplied to MRC r demanded at time t. F_{rbt} is multiplied by $tmax$, the maximum time index, minus the day the unit was required, t, also raised to a power α. This ensures that meeting a demand, no matter how late, will never be costlier than failing to meet a demand.

The third term of the objective function ensures that the demand of the first MRC is met using the fewest number of divisions:

$$C * \sum_{d=1}^{12} Bin_{q1d}$$

where Bin_{q1d} is a binary variable that equals one if division d goes to POD q, and is zero otherwise. This ensures that there are enough divisions to meet the demand for the second MRC. For example, if five divisions worth of brigades are needed at both MRCs, but brigades from six different divisions are used to meet the demands of the first MRC, only four divisions will be available to meet the second MRC demands since all brigades in a division have to go to the same MRC. This would be insufficient. Bin_{q1d} is summed over the first twelve divisions (D13 and D14 are separate brigades of D11 and D12) and multiplied by a cost coefficient, C. This coefficient must be large enough to ensure the fewest number of divisions are used to meet the demands of the first MRC and is determined by experimentation.

The last term of the objective function ensures that there is no unnecessary ship movement:

$$\epsilon \sum_{p}\sum_{q}\sum_{s}\sum_{t} V_{pqst}$$

where V_{pqst} represents the number of ships of type s, leaving POD p, at time period t, to go to POD q. ϵ is a small number that penalizes ship movements so that superfluous movements are avoided.

The objective function is subject to the constraints of the unit movement network, and the ship movement network. The unit movement network consists of Constraints 2 through 12. Constraints 8, 13, 14 and 15 make up the ship movement network.

Constraints 2 through 5 are the supply, flow balance, and demand constraints for the unit movement network. Constraints 2 are the supply constraints that ensure that

the number of units moving from their division location to all POEs does not exceed the number of units of the division stationed at the division location. Constraints 3 and 4 are flow balance constraints at the POEs and PODs, respectively, and Constraints 5 are the demand constraints.

Constraints 3 ensure that for each time period, POE, and division, the number of units that arrive at a POE equals the number of units that are sent on to a POD. Initially, units are only sent to the POD at the first MRC. However, once the second MRC begins, units are sent to either POD. Although PaMM+ creates its schedules knowing when the second MRC is going to begin, units cannot be sent to the second MRC until the MRC actually begins. There is no inventory at the POEs. That is, units are not scheduled to move to a POE until there are enough ships available to transport them to a POD. This feature assumes that units will best use predeployment time at their division locations in either training or preparation for movement.

Constraints 4 constrain the movements through the PODs. These constraints represent the flow through the POD to the different MRCs. They ensure that all units arriving at the POD are sent to meet demands defined at the MRCs.

Constraints 5 are the demand constraints. These constraints ensure that the number of units arriving over time, to meet a particular demand, plus unmet demand, equals the demand for unit type b, at time t, for MRC r.

Constraints 6 and 7 are capacity constraints at ports. Constraints 6 ensure that the maximum number of units loading over any two day period at a specific POE does not exceed the number of units that the POE has capacity to load at one time. Constraints 7 are analogous to Constraints 6, but apply to PODs.

Constraints 8 connect the two networks. First, they normalize the cargo space requirement of all units to that of an armor unit. Then, they ensure that a unit does not move from a POE to a POD unless there are ships available with sufficient amount of cargo space to carry the unit, and those ships move along the same route at the same time.

Constraints 9 and 10 ensure that all the units from a division go to the same MRC. Bin_{qd} is a binary variable that equals one if a unit from division d goes to POD q. Constraints 9 multiplies Bin_{qd} by three to ensure that all units from the same division are included in the variable Bin_{qd}. Constraints 10 ensure that all of units of each division go to only one MRC.

Constraints 11 and 12 are necessary because there are two divisions that have their units at two different locations. These constraints ensure that divisions with units at two different locations still send all of their units to the same MRC. D11 and D13 are the units of 1AD stationed in Germany and the United States. D12 and D14 are units of the 3rd Mechanized Infantry stationed in Germany and the United States.

Constraints 8 and the last three constraints make up the ship movement network. As stated earlier, Constraints 8 connect the two networks. Constraints 13 put all the ships available into inventory at time period one. PaMM will determine which POEs the ships start at based upon need. Constraints 14 and 15 are the flow balance constraints for the POEs and the PODs. Constraints 14 ensure that the number of ships leaving any POE, plus the number of ships remaining in inventory, is equal to the number of ships that arrive at the POE plus the number of ships that were

previously in inventory. Constraints 15 ensure that the number of ships leaving a POD is equal to the number of ships that arrived at the POD.

F. SEQUENTIAL SOLVING

If planners had perfect information regarding the outbreak of a second MRC at the time the first MRC began, they would be able to create optimal deployment schedules for both MRCs. However, it is unlikely planners will have perfect information, so PaMM takes this into account. That is, PaMM does not assume that the time difference between the start dates of the two MRCs is actually known. Rather, PaMM is used to explore possible deployment schedules under various hypothesized time differences. (The location of the second MRC is assumed known here.) To do this, PaMM is employed as a sequential heuristic as follows: PaMM first creates optimal deployment schedules for Army units moving to a single MRC, fixes all movement that occurs before a hypothesized start date of the second MRC, and then creates optimal deployment schedules for the rest of the first MRC and all of the second MRC. In this way, any movement that occurs to the first MRC before the second MRC begins cannot be changed, but any movement that occurs after the second MRC begins may be changed to optimize movement to both MRCs. The sequential heuristic must be run for all hypothesized time differences and results analyzed, as described in the next chapter.

III. COMPUTATIONAL RESULTS

To determine the robustness of PaMM, a test case is devised in this chapter and deployment schedules using PaMM and PaMM+ are generated and compared. If there is little difference between these schedules, the second MRC will have little effect on the deployment to the first MRC, and planners can deploy units to a single/first MRC without fear of using assets needed for the second MRC. If these schedules differ greatly, then planners must be concerned about the possibility of significant delay to a second MRC. If the delay to the second MRC for the schedules developed by PaMM+ are not significantly smaller than for the schedules developed by PaMM, planners can again feel comfortable using the schedules developed by PaMM. If PaMM+ produces schedules that have a significant decrease in delay, then planners need to consider the tradeoff between concentrating on the first MRC and the risk of a second MRC.

A. TEST CASE AND DATA

The test case for this thesis has planners developing schedules to a first MRC taking place in Northeast Asia (NEA) with a possible second MRC in Southwest Asia (SWA). Since they are not sure when the second MRC will begin, they conduct six runs of both PaMM and PaMM+ varying the time difference between the start dates of the two MRCs between 10 and 60 days, in increments of 10 days. The schedules are then compared to measure the robustness of the deployment schedules for the first MRC.

For proper comparisons, the number and type of units at each division location, the normalized cargo space requirement for each type of unit, the time it takes in days

to move from one location to another, and the demand for the first MRC remain constant for all runs. Demands for the second MRC, in quantity and unit type, also remain constant, but are shifted in time by ten days for each scenario. The input data for each division is displayed in Table 1. The demands for the first and second MRC are shown in Table 2.

Table 1. Input Data

Div	#units/ type	T_{dp} (days)	T_{pq1} (days)	T_{pq2} (days)	T_{q1r1} (days)	T_{q2r2} (days)	Mp_d
D1	1 ACR	7	21	20	2	2	0.7
D2	3 HEAVY	6	21	20	2	2	1.0
D3	3 HEAVY	6	21	20	2	2	1.0
D4	1 HEAVY	6	14	NA	2	NA	1.0
D5	3 INF	6	14	21	2	2	0.25
D6	3 AVN	16	21	18	10	10	0.3
D7	3 AA	8	21	18	2	2	0.5
D8	3 AB	7	21	18	2	2	0.4
D9	3 HEAVY	6	21	18	2	2	1.0
D10	3 INF	6	21	18	2	2	0.25
D11	2 HEAVY	6	21	12	2	2	1.0
D12	2 HEAVY	6	21	12	2	2	1.0
D13	1 HEAVY	10	21	18	2	2	1.0
D14	1 HEAVY	10	21	18	2	2	1.0

T_{i1j2}-time to move from point *i1* to point *j2*, Mp_d-proportion of cargo space to an armor unit required by division *d*, ACR-Armored Cavalry Regiment, INF-Light Infantry, AVN-Aviation, AA-Air Assault, AB-Airborne

PaMM is run using unclassified data. Unit size is battalion level for an aviation unit, and brigade/regiment level for all other units. The available units and shipping assets, and time to move between locations, are the author's

estimates of planning data obtained while working at the CAA. The space requirement for each type of unit, and the carrying capacities for each type of ship are obtained from an Army planning manual (Kelly, 1991). The demands at each theater, by unit type and time, are the author's estimate of demands from the Commander-in-Chief's operation plan. All results displayed in this thesis are unclassified.

Table 2. Unit Demands for Both MRCs

	Single/First MRC						Second MRC				
Time/ type	Day 20	Day 25	Day 26	Day 27	Day 28	Day 29	Δ + 25	Δ + 30	Δ + 31	Δ + 32	Δ + 33
Heavy	1	6	0	0	0	0	3	3	3	0	0
AVN	0	0	3	0	0	0	0	0	0	0	0
AB	0	0	0	3	0	0	0	0	0	0	0
ACR	0	0	0	0	1	0	0	0	0	0	0
INF	0	0	0	0	0	3	0	0	0	3	0
AA	0	0	0	0	0	0	0	0	0	0	3
Δ - Time difference in days between MRCs											

B. COMPUTER HARDWARE/SOFTWARE

PaMM is generated using the General Algebraic Modeling System (GAMS)(Brooke, et al., 1988). A copy of the GAMS formulation can be obtained from the author. PaMM is solved using the Optimization Subroutine Library (OSL) (IBM, 1991) using an IBM RS6000 model 590 computer. As the time difference between hypothetical start dates of the two MRCs increases, generation times increase. However, with an increase in the time difference, PaMM's solution time for

the dual MRCs decreases, presumably because more variables are fixed for each successive run. Generation and solution times for test runs are displayed in Table 3.

Table 3. Generation and Solution Times for PaMM

Difference	10 day	20 day	30 day	40 day	50 day	60 day
Generation time(secs)	312.01	309.24	309.69	383.37	466.23	549.71
Solution time(secs)	241.23	331.74	61.79	56.81	107.05	51.11

C. RESULTS FOR A SINGLE MRC

PaMM initially develops deployment schedules for the single MRC based on the type of units required at the MRC. PaMM creates the schedules trying to minimize, roughly, the delay between when a unit of a specific type is required, t, and when a responding unit actually arrives, t'. It is assumed that the longer a requirement goes without being met the more critical the delay will be, so an increasing marginal cost (penalty) is desired for each demand. Therefore, $t'-t$ is raised to a power, α, greater than one; for this thesis, $\alpha=1.5$.

The unit arrival dates to the MRC for the schedule PaMM creates are given in Table 4. This table shows the date the unit arrived, the demand it met, the delay in days, and the delay penalty. As can be seen, the total delay in days and the delay penalty for the single MRC deployment schedule is 135 days and 509.45, respectively. The total delay is dominated by the delay for aviation units: The CinC will probably want aviation units in theater as quickly as

possible, but because of the time in preparing helicopters for movement by ship, and then preparing them for use in theater, the soonest helicopters can arrive is day 48.

Table 4. Single MRC Arrival Dates and Delay

Unit - Arrival Date t'	Date Required t	Delay in days	Delay Penalty $(t'-t)^{1.5}$
D4 - 23	20	3	5.20
D5 - 25	29	0	0.0
D5 - 27	29	0	0.0
D5 - 29	29	0	0.0
D2 - 30	25	5	11.18
D2 - 30	25	5	11.18
D11 - 30	25	5	11.18
D8 - 31	27	4	8.00
D1 - 32	28	4	8.00
D2 - 32	25	7	18.52
D11 - 32	25	7	18.52
D8 - 33	27	6	14.70
D13 - 34	25	9	27.00
D8 - 35	27	8	22.63
D6 - 48	26	22	103.19
D6 - 50	26	24	117.58
D6 - 52	26	26	132.57
Total		135	509.45

D. PaMM'S RESULTS FOR DUAL MRCS

This section describes results using PaMM as a sequential heuristic to create schedules for two nearly simultaneous MRCs. In this dual-MRC scenario, the demand for the first MRC remains the same as the single MRC, and

demands for the second MRC are added. The demands for the second MRC are the same in all runs, except that they are shifted in time.

PaMM's dual-MRC results are compared to the results of the single MRC solution. Of course, all movement that occurs before the second MRC begins is the same as in the single MRC scenario. What is unexpected is that for all six runs, the deployment schedules to the first MRC are exactly the same as the deployment schedules to the single MRC. Even though not all units that end up moving to the first MRC are committed before the second MRC begins, there is no difference between the schedules for the single-MRC scenario and the schedules for the first MRC in the dual-MRC scenario. So, once again, the delay days and delay penalty for the first MRC, are 135 days and 509.45, respectively.

The second MRC deployment schedule covers those active duty units that are not deployed to the first MRC. PaMM tries to minimize the total delay for both MRCs subject to the restrictions imposed by the sequential solution procedure. The unit arrival dates to the second MRC, the date the unit is required, and the delay days and delay penalties, are displayed in Table 5. The total delay days and the total delay penalty for each run of the second MRC for the dual-MRC scenario are listed in Table 6.

The arrival dates in Table 5 are the day a unit arrives at the second MRC minus the time difference between MRCs. This is used to make it easier to see the effect the various time differences have on the arrival dates. One difference to note is the day the last unit arrives at the second MRC. For any time difference greater than or equal to 20 days, the last unit arrives on the 37th day after the second MRC starts. However, for a time difference of 10 days, the last

Table 5. Dual-MRC, Second MRC Arrival Dates and Delay

	Units/Arrival Dates - Δ						Delay Days/Delay Penalty					
t-Δ	10	20	30	40	50	60	10	20	30	40	50	60
25	D11 22	D11 25	D12 22	D12 23	D11 21	D12 23	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0
25	D11 25	D9 27	D12 25	D12 25	D11 25	D12 25	0 0.0	2 2.8	0 0.0	0 0.0	0 0.0	0 0.0
25	D2 29	D3 29	D9 27	D9 27	D9 27	D9 27	4 8.0	4 8.0	2 2.8	2 2.8	2 2.8	2 2.8
30	D2 29	D3 30	D2 29	D9 29	D2 29	D3 29	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0
30	D2 31	D9 31	D2 30	D3 30	D9 29	D3 29	1 1.0	1 1.0	0 0.0	0 0.0	0 0.0	0 0.0
30	D9 33	D3 32	D9 31	D3 30	D2 31	D9 29	3 5.2	2 2.8	1 1.0	0 0.0	1 1.0	0 0.0
31	D13 33	D9 33	D2 32	D9 31	D2 31	D3 31	2 2.8	2 2.8	1 1.0	0 0.0	0 0.0	0 0.0
31	D9 35	D13 33	D9 33	D3 32	D9 33	D9 31	4 8.0	2 2.8	2 2.8	1 1.0	2 2.8	0 0.0
31	D9 37	D11 36	D14 33	D14 33	D13 33	D14 33	6 14.7	5 11.2	2 2.8	2 2.8	2 2.8	2 2.8
32	D10 27	D10 27	D10 27	D10 28	D10 28	D10 27	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0
32	D10 29	D10 29	D10 29	D10 30	D10 30	D10 29	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0
32	D10 31	D10 31	D10 32	D10 32	D10 32	D10 31	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0
33	D7 39	D7 29	D7 29	D7 33	D7 31	D7 33	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0	0 0.0
33	D7 41	D7 35	D7 35	D7 35	D7 35	D7 35	8 22.6	2 2.8	2 2.8	2 2.8	2 2.8	2 2.8
33	D7 43	D7 37	D7 37	D7 37	D7 39	D7 37	10 31.6	4 8.0	4 8.0	4 8.0	6 14.7	4 8.0

unit does not arrive until the 43rd day after the MRC starts. This helps explain why the total delay days and delay penalty for a time difference of 10 days is so much higher than the others. The results of PaMM are now compared to the results obtained from PaMM+.

Table 6. Delay Days and Delay Penalty for the Second MRC in a Dual-MRC Scenario

	10 Day	20 Day	30 Day	40 Day	50 Day	60 Day
Delay Days	44 days	24 days	14 days	11 days	15 days	10 days
Delay Penalty	108.67	42.32	21.31	17.49	27.01	16.49

E. RESULTS OF PaMM+

PaMM+ solves the dual-MRC scenario assuming the start date and location of the second MRC are known when the first MRC begins. PaMM+ is solved to measure the robustness of the schedules created by PaMM. PaMM+ was run for all six time differences. The arrival dates to the first MRC for all six runs are listed in Table 7.

Having perfect information yields only two significantly different deployment schedules in the six cases. For time differences of 20, 30 and 40 days the deployment schedules to the first MRC produced by PaMM+ are very similar to the schedules produced by PaMM. For differences of 10, 50 and 60 days, however, the deployment schedules have both the heavy units stationed at Fort Hood, D2 and D3, going to the first MRC, and sends both the units stationed in Germany to the second MRC, instead of sending one unit from each location to each MRC. Although this is an optimal solution

Table 7. PaMM+, First MRC Arrival Dates

10 DAY DIFFERENCE	20 DAY DIFFERENCE	30 DAY DIFFERENCE	40 DAY DIFFERENCE	50 DAY DIFFERENCE	60 DAY DIFFERENCE
D4 - 23	D4 - 23	D4 - 23	D4 - 25	D4 - 23	D4 - 23
D5 - 24	D5 - 24	D5 - 23	D5 - 25	D5 - 24	D5 - 24
D5 - 26	D5 - 26	D5 - 25	D5 - 27	D5 - 26	D5 - 26
D5 - 29	D5 - 28	D5 - 27	D5 - 29	D5 - 28	D5 - 29
D3 - 30	D2 - 30	D2 - 30	D2 - 30	D2 - 30	D3 - 30
D3 - 30	D2 - 30	D2 - 30	D2 - 30	D2 - 30	D3 - 30
D8 - 31	D11 - 30	D12 - 30	D12 - 30	D8 - 31	D8 - 31
D1 - 32	D8 - 31	D8 - 31	D8 - 31	D2 - 32	D2 - 32
D3 - 32	D1 - 32	D2 - 32	D1 - 32	D3 - 32	D2 - 32
D8 - 33	D2 - 32	D12 - 32	D2 - 32	D8 - 33	D8 - 33
D2 - 34	D11 - 32	D8 - 33	D12 - 32	D3 - 34	D2 - 34
D2 - 34	D8 - 33	D1 - 34	D8 - 33	D3 - 34	D3 - 34
D8 - 35	D13 - 34	D8 - 35	D14 - 34	D8 - 35	D8 - 35
D2 - 36	D8 - 35	D14 - 35	D8 - 35	D1 - 36	D1 - 36
D6 - 48	D6 - 48	D6 - 48	D6 - 48	D6 - 48	D6 - 48
D6 - 50	D6 - 50	D6 - 50	D6 - 50	D6 - 50	D6 - 50
D6 - 52	D6 - 52	D6 - 52	D6 - 52	D6 - 52	D6 - 52

for the dual-MRC scenario, it does cause the units going tothe first MRC to arrive a little later. The delay days and delay penalties for time differences of 10, 50 and 60 days for the first MRC are in shown Table 8. The total delay days for the first MRC increase from 135 days (penalty 509.45) to 143 days (penalty 543.23), 143 days (penalty 539.90) and 143 days (penalty 539.90) for time differences of 10, 50 and 60 days, respectively. However, since PaMM+ creates different schedules than PaMM, the delay to the second MRC must be checked to see if there is any significant savings.

Table 8. PaMM+, Delay for the First MRC

	Unit/Arrival Dates			Delay Day/Delay Penalty		
t	10 t'	50 t'	60 t'	10	50	60
20	D4 - 23	D4 - 23	D4 - 23	3/5.20	3/5.20	3/5.20
25	D3 - 30	D2 - 30	D3 - 30	5/11.18	5/11.18	5/11.18
25	D3 - 30	D2 - 30	D3 - 30	5/11.18	5/11.18	5/11.18
25	D3 - 32	D2 - 32	D2 - 32	7/18.52	7/18.52	7/18.52
25	D2 - 34	D3 - 32	D2 - 32	9/27.00	7/18.52	7/18.52
25	D2 - 34	D3 - 34	D2 - 34	9/27.00	9/27.00	9/27.00
25	D2 - 36	D3 - 34	D3 - 34	11/36.48	9/27.00	9/27.00
26	D6 - 48	D6 - 48	D6 - 48	22/103.19	22/103.19	22/103.19
26	D6 - 50	D6 - 50	D6 - 50	24/117.58	24/117.58	24/117.58
26	D6 - 52	D6 - 52	D6 - 52	26/132.57	26/132.57	26/132.57
27	D8 - 31	D8 - 31	D8 - 31	4/8.00	4/8.00	4/8.00
27	D8 - 33	D8 - 33	D8 - 33	6/14.70	6/14.70	6/14.70
27	D8 - 35	D8 - 35	D8 - 35	8/22.63	8/22.63	8/22.63
28	D1 - 32	D1 - 36	D1 - 36	4/8.00	4/22.63	4/22.63
29	D5 - 24	D5 - 24	D5 - 24	0/0.00	0/0.00	0/0.00
29	D5 - 26	D5 - 26	D5 - 26	0/0.00	0/0.00	0/0.00
29	D5 - 29	D5 - 28	D5 - 29	0/0.00	0/0.00	0/0.00
Delay Days/Penalty for PaMM+				143/543.23	143/539.90	143/539.90
Delay Days/Penalty for PaMM				135/509.45	135/509.45	135/509.45
Difference (Increase in Delay)				8/33.78	8/30.45	8/30.45

The arrival dates to the second MRC for PaMM+ are displayed in Table 9. Once again, the date in the table is the day the unit arrives after the second MRC begins. Since there are significantly different schedules for the first MRC for time differences of 10, 50 and 60 days only, only

Table 9. PaMM+, Second MRC Arrival Dates

10 DAY DIFFERENCE	20 DAY DIFFERENCE	30 DAY DIFFERENCE	40 DAY DIFFERENCE	50 DAY DIFFERENCE	60 DAY DIFFERENCE
D12 - 21	D12 - 23	D11 - 21	D11 - 24	D11 - 21	D12 - 21
D11 - 23	D12 - 25	D11 - 24	D11 - 26	D12 - 23	D11 - 23
D12 - 25	D9 - 27	D9 - 27	D9 - 27	D11 - 25	D11 - 25
D10 - 28	D10 - 28	D10 - 27	D10 - 28	D9 - 27	D9 - 27
D10 - 30	D3 - 29	D3 - 29	D3 - 29	D10 - 27	D10 - 27
D11 - 30	D3 - 29	D3 - 29	D3 - 29	D12 - 27	D12 - 27
D10 - 32	D9 - 29	D9 - 29	D9 - 29	D9 - 29	D9 - 29
D9 - 33	D10 - 30	D10 - 30	D10 - 30	D10 - 29	D10 - 29
D13 - 33	D3 - 31	D3 - 31	D3 - 31	D9 - 31	D9 - 31
D14 - 33	D9 - 31	D7 - 31	D9 - 31	D10 - 31	D10 - 32
D9 - 35	D10 - 32	D10 - 32	D10 - 32	D7 - 33	D7 - 33
D9 - 37	D7 - 33	D7 - 33	D7 - 33	D13 - 33	D13 - 33
D7 - 39	D14 - 33	D13 - 33	D13 - 33	D14 - 33	D14 - 33
D7 - 41	D7 - 35	D7 - 37	D7 - 35	D7 - 35	D7 - 35
D7 - 43	D7 - 37	D7 - 39	D7 - 37	D7 - 37	D7 - 37

the delay for these time differences is calculated and displayed in Table 10. These results are compared to the delay from PaMM for the same time differences.

As can be seen, the delay days for PaMM+ is 42 days (penalty 104.88), 10 days (penalty 16.49) and 10 days (penalty 16.49), for time differences of 10, 50 and 60 days, respectively. The delay for PaMM for these same time differences is 44 days (penalty 108.67), 15 days (penalty 27.01) and 10 days (penalty 16.49). PaMM+'s schedules decrease the delay to the second MRC by a total of 2 days (penalty 3.79), 5 days (penalty 10.52) and 0 days (penalty 0). Therefore, since there is not a significant gain using

the deployment schedules PaMM+ creates, planners could confidently use the schedules PaMM creates for the dual-MRC scenario.

Table 10. PaMM+, Delay for the Second MRC

	Unit Arrival Dates			Delay		
t	10 t'	50 t'	60 t'	10	50	60
25	D12 - 21	D11 - 21	D12 - 21	0/0.00	0/0.00	0/0.00
25	D11 - 23	D12 - 23	D11 - 23	0/0.00	0/0.00	0/0.00
25	D12 - 25	D11 - 25	D11 - 25	0/0.00	0/0.00	0/0.00
30	D11 - 30	D9 - 27	D9 - 27	0/0.00	0/0.00	0/0.00
30	D9 - 33	D12 - 27	D12 - 27	3/5.20	0/0.00	0/0.00
30	D13 - 33	D9 - 29	D9 - 29	3/5.20	0/0.00	0/0.00
31	D14 - 33	D9 - 31	D9 - 31	2/2.83	0/0.00	0/0.00
31	D9 - 35	D13 - 33	D13 - 33	4/8.00	2/2.83	2/2.83
31	D9 - 37	D14 - 33	D14 - 33	6/14.70	2/2.83	2/2.83
32	D10 - 28	D10 - 27	D10 - 27	0/0.00	0/0.00	0/0.00
32	D10 - 30	D10 - 29	D10 - 29	0/0.00	0/0.00	0/0.00
32	D10 - 32	D10 - 31	D10 - 32	0/0.00	0/0.00	0/0.00
33	D7 - 39	D7 - 33	D7 - 33	6/14.70	0/0.00	0/0.00
33	D7 - 41	D7 - 35	D7 - 35	8/22.63	2/2.83	2/2.83
33	D7 - 43	D7 - 37	D7 - 37	10/31.62	4/8.00	4/8.00
Total Delay for PaMM+				42/104.88	10/16.49	10/16.49
Total Delay for PaMM				44/108.67	15/27.01	10/16.49
Difference (Decrease in Delay)				-2/-3.79	-5/-10.52	0/0.00

IV. CONCLUSIONS

This thesis presents an integer programming model and solution procedure, called "PaMM" (Plural MRC Model), that creates deployment schedules for active duty Army units moving to two nearly simultaneously MRCs (Major Regional Conflicts). Unlike models currently used by the Army, PaMM creates deployment schedules without predesignating specific units to meet specific demands. Rather, PaMM uses the demands for units of specific types at specified dates and locations from the Commander-in-Chief's operation plan, and creates schedules by selecting which unit will be used to meet these demands.

PaMM routes units from their home stations to ports of embarkation (POEs), from POEs to ports of debarkation (PODs) by sealift, and from PODs to the in-theater locations at which the units are required. PaMM also routes the sealift assets that carry the units between POEs and PODs to ensure that the deployment schedules are feasible with respect to shipping capacity. Demands need not be met on time. The objective of the model is to minimize a function of the time between the desired unit arrival dates and the actual arrival dates, i.e., delay.

If planners had perfect information regarding the outbreak of a second MRC at the time the first MRC began, they would be able to create optimal deployment schedules for both MRCs. PaMM plus perfect information, "PaMM+," creates such schedules. However, it is unlikely planners will have perfect information, so PaMM takes this into account. That is, PaMM does not assume that the time difference between the start dates of the two MRCs is actually known. Rather, PaMM is used to explore possible

deployment schedules under various time differences. To do this, PaMM is employed as a sequential heuristic as follows: PaMM first creates optimal deployment schedules for Army units moving to a single MRC, fixes all movement that occurs before a hypothesized start date of the second MRC, and then creates optimal deployment schedules for the rest of the first MRC and all of the second MRC. This process is repeated for all hypothesized start dates for the second MRC and results compared.

PaMM is tested using a hypothetical scenario where there is a rebel uprising in Korea (the first MRC), followed by an attack on Saudi Arabia (the second MRC). The time differences between the start dates of the MRCs are 10, 20, 30, 40, 50, and 60 days. For the single MRC, and for the first MRC deployment schedule in the dual-MRC scenario, PaMM creates a deployment schedule with a delay of 135 days and a delay penalty of 509.45.

To establish the robustness of PaMM's Schedules, PaMM+ is run on the same data. PaMM+ creates only two substantially different solutions for the six time differences. Where the unit delays are 20, 30 and 40 days, PaMM+ creates deployment schedules very similar to PaMM. However, with time differences of 10, 50, and 60 days, the deployment schedules are different. The delays for the schedules PaMM+ creates for the latter time differences are 143 days (penalty 543.23), 143 days (penalty 539.90) and 143 days (penalty 539.90). Since PaMM+'s results are different for these time differences, the delay for the second MRC is compared for PaMM and PaMM+.

For time differences of 10, 50 and 60 days, PaMM's schedules for the second MRC have a delay of 44 days (penalty 108.67), 15 days (penalty 27.01) and 10 days

(penalty 16.49). PaMM+'s schedules have a delay of 42 days (penalty 104.88), 10 days (penalty 16.49) and 10 days (penalty 16.49) for the same time differences. PaMM+ decreases delay by 2 days (penalty decrease 3.79), 5 days (penalty decrease 10.52) and 0 days (penalty decrease 0) for the second MRC using the different schedules. Since the savings to the second MRC are not significant, the deployment schedule for the first MRC could be implemented with great confidence that a good deployment schedule for the second MRC could be created and implemented if that MRC were to break out. However, these favorable results must be confirmed with more realistic, classified scenarios.

To provide even more robust schedules, PaMM could be enhanced. To make the ship modeling more realistic, a separate ship speed could be used for each different type of ship. This would allow planners to not only create better deployment schedules for the units, but would also allow planners to use PaMM to develop ship schedules. Another enhancement that could be made would be to increase the number of types of units. Currently, PaMM aggregates armor, mechanized infantry and cavalry divisions into heavy units. Although these units may have the same cargo capacity requirements, they all have unique make-ups and capabilities. Depending on the situation, one type of heavy unit might be better suited for a mission than another type. By increasing the number of unit types modeled, PaMM would be required to select from a more restricted set of divisions to meet certain demands, which could result in more suitable schedules. Testing would be required to determine if the enhancements suggested above are computationally tractable, but such testing would not be difficult.

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